

## SPITZER FAR-INFRARED DETECTIONS OF COLD CIRCUMSTELLAR DISKS

P. S. SMITH<sup>1</sup>, D. C. HINES<sup>2</sup>, F. J. LOW<sup>1</sup>, R. D. GEHRZ<sup>3</sup>, E. F. POLOMSKI<sup>3</sup>, & C. E. WOODWARD<sup>3</sup>*To appear in The Astrophysical Journal Letters*

## ABSTRACT

Observations at 70  $\mu\text{m}$  with the *Spitzer Space Telescope* have detected several stellar systems within 65 pc of the Sun. Of 18 presumably young systems detected in this study, as many as 15 have 70  $\mu\text{m}$  emission in excess of that expected from their stellar photospheres. Five of the systems with excesses are members of the Tucanae Association. The 70  $\mu\text{m}$  excesses range from a factor of  $\sim 2$  to nearly 30 times the expected photospheric emission from these stars. In contrast to the 70  $\mu\text{m}$  properties of these systems, there is evidence for an emission excess at 24  $\mu\text{m}$  for only HD 3003, confirming previous results for this star. The lack of a strong 24  $\mu\text{m}$  excess in most of these systems suggests that the circumstellar dust producing the IR excesses is relatively cool ( $T_{\text{dust}} \lesssim 150$  K) and that there is little IR-emitting material within the inner few AU of the primary stars. Many of these systems lie close enough to Earth that the distribution of the dust producing the IR excesses might be imaged in scattered light at optical and near-IR wavelengths.

*Subject headings:* infrared: stars—circumstellar matter—planetary systems: formation

## 1. INTRODUCTION

One of the major scientific objectives of the *Spitzer Space Telescope* (*Spitzer*; Werner et al. 2004) is to identify and characterize circumstellar dust around a broad range of stars, both in spectral type and age. In this regard, the unprecedented sensitivity and spatial resolution of *Spitzer* has proved to be a dramatically successful tool in the infrared study of planetary debris systems (see, e.g., Meyer et al. 2004; Uchida et al. 2004; Gorlova et al. 2004; Jura et al. 2004; Stapelfeldt et al. 2004; Sloan et al. 2004; Rieke et al. 2005; Beichman et al. 2005a; Beichman et al. 2005b; Chen et al. 2005; Su et al. 2005; Uzpen et al. 2005; Stauffer et al. 2005; Low et al. 2005; Kim et al. 2005; Bryden et al. 2006; Hines et al. 2006). These early investigations using data from *Spitzer* have generally shown that “warm” material resulting in a strong signature at 24  $\mu\text{m}$ , indicating the presence of dust within the region where terrestrial planet formation can take place, is quite rare for stars over  $\sim 10$  million years (Myr) old. Also, the frequency of finding colder material around stars of any age is higher than finding dust that gives rise to an emission excess at 24  $\mu\text{m}$ . For instance, a study of the TW Hya Association (TWA) by Low et al. (2005) found that only one of 15 objects not previously detected by the *Infrared Astronomical Satellite* (*IRAS*), TWA 7, shows evidence for excess emission at 24  $\mu\text{m}$ . However, based on the 70  $\mu\text{m}$  flux density measurement of TWA 7, the 24  $\mu\text{m}$  excess is consistent with emission from dust at  $T = 80$  K located at least  $\sim 7$  AU from the star.

The mixture of objects within the TWA having little or no 24  $\mu\text{m}$  excess, with a few objects (e.g., TW Hya and HD 98800B) of the same age having among the strongest warm excesses observed, is a powerful example of how rapidly dust within  $\sim 5$ –10 AU of the stellar

primary can be removed from these systems. Given that the TWA is estimated to have an age of only 8–10 Myr, it is clear that dust destruction mechanisms near the stellar primary, such as planet building and the Poynting-Robertson effect, can become dominant or are possibly even completed early in the formation of these systems (see, e.g., Strom, Edwards, & Skrutskie 1993, and references therein). In fact, recent 3.6–24  $\mu\text{m}$  *Spitzer* results for more distant stellar associations and clusters, ranging in age from  $\sim 2$ –12 Myr, begin to chronicle the rapid evolution of the inner dust disk (e.g., Hartmann et al. 2005; Sicilia-Aguilar, et al. 2006; Lada et al. 2006).

We have used *Spitzer* to survey 112 stars that are close enough to Earth that their distances have been measured by the *Hipparcos* Satellite and exhibit some evidence that they are younger than  $\sim 40$  Myr old. Low et al. (2005) summarize the general selection criteria for this sample. In this *Letter* we identify 18 stars in the sample that have been detected at 70  $\mu\text{m}$ . Three of the detections are consistent with the level of emission expected from the stellar photosphere. Most of the remaining 15 systems show substantial IR excesses, identifying them as containing circumstellar material with  $T \lesssim 150$  K.

## 2. OBSERVATIONS AND RESULTS

Photometry at 24  $\mu\text{m}$  and 70  $\mu\text{m}$  of 112 stars within  $\sim 100$  pc of the Sun was acquired using the Multi-band Imaging Photometer for *Spitzer* (MIPS; Rieke et al. 2004). The observations and reductions closely follow those described in Low et al. (2005). All of the 70  $\mu\text{m}$  observations were made using the wide-field, default scale observing mode. Since publication of the MIPS observations of the TWA, the photometric calibration conversion factors for the MIPS bandpasses have been updated. For the current study, we use these revised factors, which are:  $1.05 (\pm 0.04) \times 10^{-3}$  mJy arcsec<sup>-2</sup>  $DU^{-1}$  and  $16.5 (\pm 1.2)$  mJy arcsec<sup>-2</sup>  $DU^{-1}$  for the 24  $\mu\text{m}$  and 70  $\mu\text{m}$  bandpasses, respectively (Engelbracht 2006), where 1 mJy =  $10^{-26}$  erg cm<sup>-2</sup> s<sup>-1</sup> Hz<sup>-1</sup> and a data unit ( $DU$ ) is the instrumental output produced by the MIPS “Data Analysis Tool” (DAT) reduction pipeline

<sup>1</sup> Steward Observatory, The University of Arizona, Tucson, AZ 85721; psmith, flow@as.arizona.edu

<sup>2</sup> Space Science Institute, 3100 Marine Street, Suite A353, Boulder, CO 80303; dean.hines@colorado.edu

<sup>3</sup> University of Minnesota, Department of Astronomy, Minneapolis, MN 55455; gehrz, elwood, chelsea@astro.umn.edu

(Gordon et al. 2005). Uncertainties quoted for the MIPS photometry include both the measurement precision and the uncertainties in the photometric calibration factors.

Nineteen of 112 stars in the sample have 70  $\mu\text{m}$  detections with signal-to-noise ratios ( $S/N$ )  $\geq 5$ , where  $S/N$  is the measurement precision defined by the signal measured from the object divided by the noise (per pixel) in the background annulus, scaled to the photometric aperture. The 24  $\mu\text{m}$  and 70  $\mu\text{m}$  flux density measurements for 18 of these stars are summarized in Table 1. The *Spitzer* observations of HD 181327, a suspected member of the Tucanae Association having an IR excess previously detected by *IRAS*, are reported in Schneider et al. (2006). Also listed in Table 1 is the 70  $\mu\text{m}$  detection  $S/N$ . All 18 stars have a detection  $S/N > 100$  at 24  $\mu\text{m}$  and the listed photometric uncertainties are dominated by the uncertainty in the flux calibration factor for this bandpass.

Figure 1 plots a color-color diagram of the stars that shows the range in the strengths of IR emission at both 24  $\mu\text{m}$  and 70  $\mu\text{m}$ . Except for the IR excess identified previously by *IRAS* for HD 3003 (Whitelock et al. 1989), there is little evidence for excess IR emission at 24  $\mu\text{m}$  for the sample. For comparison, we include the previous results for TWA 7 in Figure 1 (Low et al. 2005). This star exhibits a 24  $\mu\text{m}$  emission excess that accounts for  $\sim 40\%$  of the total measured 24  $\mu\text{m}$  flux density. Even an excess this small produces a much larger  $F_{24\mu\text{m}}/F_{K_s}$  than is observed for all of the stars included in Figure 1 except for HD 3003. Indeed, the remaining 17 systems are located comfortably between the high-temperature Rayleigh-Jeans limit for  $F_{24\mu\text{m}}/F_{K_s}$  and the flux density ratio expected from a stellar photosphere with  $T_{\text{eff}} = 3000$  K.

There is a possibility at 70  $\mu\text{m}$  that flux from extragalactic sources also falls within the 70''-diameter circular photometric aperture, thereby resulting in a false detection or an overestimation of the far-IR emission from a stellar system. Based on *Spitzer* 70  $\mu\text{m}$  source counts (Dole et al. 2004), we estimate that for each star there is  $\sim 1\%$  chance that an extragalactic source with  $F_{70\mu\text{m}} > 15$  mJy can be found within the aperture. Therefore, we can expect a few cases where the measurements of stars in a sample of over 100 are confused with background sources. In fact, there is evidence for at least some contribution by background objects to the measured 70  $\mu\text{m}$  flux densities for four stars: HD 2884, HD 11507, BD+40°2208, and HD 124498. For both BD+40°2208 and HD 124498, there are two faint sources within 20'' of the stars in the 24  $\mu\text{m}$  images that could contribute to the total flux measured at 70  $\mu\text{m}$ . The displacement of the centroid of the 70  $\mu\text{m}$  flux by about 10'' (1 pixel) is consistent with the two background sources providing most of the measured flux instead of BD+40°2208. Although the centroid of the flux for HD 124498 is at the expected location on the 70  $\mu\text{m}$  array, we cannot rule out the possibility that a fraction of the signal is from the sources seen at 24  $\mu\text{m}$ . The centroid of HD 11507 is offset from the nominal 70  $\mu\text{m}$  array location by  $3\times$  the  $\sim 0.3$  pixel (rms) deviations observed relative to the stars' positions on the 24  $\mu\text{m}$  detector. In this case, the position angle and magnitude of the offset is consistent with at least half of the 70  $\mu\text{m}$  flux coming from a source apparent at 24  $\mu\text{m}$  that is  $\sim 20''$  away

from HD 11507. Likewise, the 70  $\mu\text{m}$  source measured for HD 2884, is displaced from the aperture center by about 1 pixel, but there is no corresponding source seen at 24  $\mu\text{m}$ . The values listed in Table 1 for  $F_{70\mu\text{m}}$  for these four stars can be considered upper limits because of the uncertain contribution by possible background sources.

In contrast to the lack of strong 24  $\mu\text{m}$  excesses in the sample, only three stars (HD 2885, HD 98230, and HD 193924) have measured 70  $\mu\text{m}$  flux densities that are fully consistent with emission from their photospheres. The 11 objects that show no evidence for contamination of their far-IR photometry by background sources have 70  $\mu\text{m}$  emission ranging from  $\sim 2$ –30 times greater than expected from a stellar photosphere (Figure 1), implying thermal emission from dust residing in circumstellar disks. The broad-band IR spectra of three systems that show a representative range of emission strengths at 70  $\mu\text{m}$  are displayed in Figure 2.

### 3. DISCUSSION

Table 2 summarizes the upper limits for the temperature ( $T_D$ ) and minimum distance from the stellar primary ( $R_D$ ) of the circumstellar dust detected by *Spitzer* assuming blackbody dust grains in thermal equilibrium with the stellar radiation field. Except where noted in the table,  $T_D$  is an estimated color temperature based on the flux ratio of the excess emission at 24  $\mu\text{m}$  and 70  $\mu\text{m}$ . For most systems, the presence of dust emission at 24  $\mu\text{m}$  is uncertain and we have assigned an extreme upper limit on the strength of any possible flux excess at this wavelength by setting the photospheric flux density to the value dictated by the Rayleigh-Jeans limit based on the 2MASS  $K_s$ -band flux density [i.e.,  $F_{24\mu\text{m}} = (\lambda_{K_s}/\lambda_{24\mu\text{m}})^2 F_{K_s}$ ; see Figure 1]. The upper limit chosen for the 24  $\mu\text{m}$  excess leads to an upper limit for the temperature of the emitting material, and in turn, a lower limit for the distance from the star of the dust.

The fraction of 70  $\mu\text{m}$  excess detections in the overall sample is  $\sim 10$ –15% (12–16 of 112 objects). Included in our MIPS survey are 22 stars believed to be members of the Tucanae Association (Zuckerman & Webb 2000; Zuckerman, Song, & Webb 2001). Eight of these systems, including HD 181327 (Schneider et al. 2006) and HD 2884 (see §2), are detected at 70  $\mu\text{m}$ , although the measurements for HD 2885 and HD 193924 are consistent with purely photospheric emission. The *Spitzer* observations also confirm the detection of HD 3003 at 25  $\mu\text{m}$  by *IRAS*, and this object is the only member of the Tucanae Association that shows emission from dust at  $T_D > 200$  K as suggested by the *Spitzer* and *IRAS* 12–70  $\mu\text{m}$  data (see Figure 2).

Comparison of the results for the  $\sim 20$ –40 Myr Tucanae Association with those for the younger  $\sim 8$ –10 Myr TWA shows about a three-fold decrease in the fraction of detected 24  $\mu\text{m}$  excesses for the older systems.<sup>4</sup> The Tucanae Association has about the same fraction of detected emission excesses at 70  $\mu\text{m}$  as seen in the TWA. Cold material, however, is detected by *Spitzer* around Tucanae systems having spectral types B–G, not the late-type stars that also dominate the membership of the TWA.

<sup>4</sup> Both associations have similar mean distance from the Sun,  $d \sim 40$ –60 pc.

Finally, we note that the relative proximity of these systems to the Sun, together with the fact that the observed 70  $\mu\text{m}$  flux excesses reveal relatively cold material, imply that it is possible to image the distribution of the circumstellar dust in scattered light at optical and near-IR wavelengths for many of these objects with current high-resolution capabilities. In the last column of Table 2, we list the lower limit for the angular extent of the IR-emitting dust. For most systems, the dust is at least  $0''.1$ – $0''.2$  from the stars. Indeed, recent *Hubble Space Telescope* observations of HD 181327 using the NICMOS and ACS coronagraphs have revealed the circumstellar disk in scattered optical and near-IR light, with peak intensity at  $\sim 1''.7$  from the star (Schneider et al. 2006).

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## REFERENCES

- Beichman, C. A., et al. 2005a, *ApJ*, 622, 1160  
 Beichman, C. A., et al. 2005b, *ApJ*, 626, 1061  
 Bryden, G., et al. 2006, *ApJ*, 636, 1098  
 Chen, C. H., Jura, M., Gordon, K. D., & Blaylock, M. 2005, *ApJ*, 623, 493  
 Dole, H., et al. *ApJS*, 154, 87  
 Engelbracht, C. W. 2006, private communication  
 Gordon, K. D., et al. 2005, *PASP*, 117, 503  
 Gorlova, N., et al. 2004, *ApJS*, 154, 448  
 Hartmann, L., et al. 2005, *ApJ*, 629, 881  
 Høg, E., et al. 2000, *A&A*, 355, L27  
 Hines, D. C., et al. 2006, *ApJ*, 638, 1070  
 Jura, J. S., et al. 2004, *ApJS*, 154, 453  
 Kim, J. S., et al. 2005, *ApJ*, 632, 659  
 Kurucz, R. L. 1979, *ApJS*, 40, 1  
 Lada, C. J., et al. 2006, *AJ*, 131, 1574  
 Low, F. J., Smith, P. S., Werner, M., Chen, C., Krauss, V., Jura, M., & Hines, D. C. 2005, *ApJ*, 631, 1170  
 Meyer, M. R., et al. 2004, *ApJS*, 154, 422  
 Moshir, M., et al. 1992, Explanatory Supplement to the *IRAS* Faint Source Survey, Version 2.0, California Institute of Technology, JPL D-10015  
 Perryman, M. A. C., et al. 1997, *A&A*, 323, L49  
 Rieke, G. H., et al. 2005, *ApJ*, 620, 1010  
 Rieke, G. H., et al. 2004, *ApJS*, 154, 25  
 Santos, N. C., et al. 2003, *A&A*, 406, 373  
 Schneider, G., et al. 2006, *ApJ*, submitted  
 Sicilia-Aguilar, A. et al. 2006, *ApJ*, 638, 897  
 Sloan, G. C., et al. 2004, *ApJ*, 614, 77L  
 Stapelfeldt, K. R., et al. 2004, *ApJS*, 154, 458  
 Stauffer, J. R., et al. 2005, *AJ*, 130, 1834  
 Strom, S. E., Edwards, S., & Skrutskie, M. F. 1993, in *Protostars and Planets III*, ed. E. H. Levy & J. I. Lunine (Tucson: The University of Arizona Press), 837  
 Su, K. Y. L., et al. 2005, *ApJ*, 628, 487  
 Uchida, K. I., et al. 2004, *ApJS*, 154, 439  
 Uzpen, B., et al. 2005, *ApJ*, 629, 512  
 Whitelock, P. A., et al. 1989, *MNRAS*, 241, 393  
 Werner, M. W., et al. 2004, *ApJS*, 154, 1  
 Zuckerman, B., Song, I., & Webb, R. A. 2001, *ApJ*, 559, 388  
 Zuckerman, B., & Webb, R. A., 2000, *ApJ*, 535, 959

TABLE 1  
EIGHTEEN STELLAR SYSTEMS DETECTED AT 70 MICRONS

Star	HIP <sup>a</sup>	Spectral Type <sup>b</sup>	distance (pc) <sup>a</sup>	$V_T$ <sup>a</sup>	$K_s$ <sup>c</sup>	$F_{24\mu\text{m}}$ (mJy)	$F_{70\mu\text{m}}$ (mJy)	$(S/N)_{70\mu\text{m}}$
HD 1466 <sup>d</sup>	1481	F8/G0V	41 ± 1	7.53	6.15	32.9 ± 1.3	22.4 ± 3.3	7.7
HD 2884 <sup>d,e</sup>	2484	B9V	43 ± 1	4.33	4.48	101.7 ± 8.6	56.8 ± 5.2 <sup>f</sup>	17.2
HD 2885 <sup>d,e</sup>	2487	A2V	53 ± 13	4.53	4.11	156.1 ± 4.5	18.5 ± 3.8	5.2
HD 3003 <sup>d,e</sup>	2578	A0V	46 ± 1	5.08	4.99	223.9 ± 9.0	62.2 ± 5.1	22.8
HD 11507	8768	K7	11.1 ± 0.2	9.07	5.18	67.6 ± 2.7	24.2 ± 1.9 <sup>f</sup>	26.6
BD+40°2208	46383	K5	32 ± 2	9.99	6.62	18.7 ± 0.8	27.6 ± 3.0 <sup>f</sup>	12.0
HD 82443	46843	K0V	17.8 ± 0.3	7.16	5.12	72.3 ± 2.9	29.5 ± 4.4	7.7
HD 84075	47135	G2V	63 ± 3	8.65	7.16	12.4 ± 0.5	34.4 ± 3.7	12.4
HD 95650	53985	M0	11.7 ± 0.2	9.83	5.69	44.6 ± 1.8	14.8 ± 2.9	5.5
HD 98230 <sup>e</sup>	55203	F8.5V	7.3 ± 0.9	3.79	2.14	968.5 ± 38.7	93.9 ± 10.0	12.5
BD+21°2486 <sup>e</sup>	63942	K5	18.6 ± 0.9	9.62	6.04	34.4 ± 1.4	44.7 ± 3.9	18.9
HD 124498 <sup>e</sup>	69562	K4V	26 ± 5	10.52	6.60	20.8 ± 0.8	118.4 ± 14.3 <sup>f</sup>	44.0
HD 177171 <sup>d,e</sup>	93815	F7V	52 ± 2	5.24	4.06	217.4 ± 8.7	45.1 ± 5.5	10.2
HD 180134	94858	F7V	46 ± 1	6.42	5.10	63.8 ± 2.7	16.2 ± 3.4	5.1
HD 192263 <sup>e,g</sup>	99711	K2V	19.9 ± 0.4	7.88	5.54	40.8 ± 1.6	28.7 ± 2.9	13.7
HD 193924 <sup>d,e</sup>	100751	B2IV	56 ± 2	1.90	2.48	628.5 ± 25.1	63.5 ± 6.5	13.5
HD 202917 <sup>d</sup>	105388	G5V	46 ± 2	8.74	6.91	20.0 ± 0.8	35.1 ± 3.8	12.3
HD 218340	114236	G3V	57 ± 2	8.52	6.95	11.6 ± 0.5	32.0 ± 3.5	11.7

<sup>a</sup>Hipparcos designations, distances, and visual *Tycho* ( $V_T$ ) magnitudes are from the *Hipparcos* and *Tycho* Catalogs (Perryman et al. 1997; Høg et al. 2000).

<sup>b</sup>Spectral type is quoted from the *SIMBAD* Astronomical Database.

<sup>c</sup>Apparent  $K_s$  magnitudes are from the Two-Micron All Sky Survey (2MASS) Point Source Catalog.

<sup>d</sup>Probable or possible members of the Tucanae Association (Zuckerman & Webb 2000).

<sup>e</sup>Unresolved double stars or spectroscopic binary systems. In each case, the total magnitudes and flux densities are listed for the systems.

<sup>f</sup>Possible flux from background sources included within the photometry aperture. These values should be considered upper limits to the 70  $\mu\text{m}$  flux density possibly detected from the stellar system.

<sup>g</sup>Possible planetary system detected (Santos et al. 2003).

TABLE 2  
PROPERTIES OF THE CIRCUMSTELLAR DUST

Star	$T_D$ (K) <sup>a</sup>	$R_D$ (AU)	$\theta_D$ (")
HD 1466	< 115	> 7.2	> 0.18
HD 2884	< 90	> 65	> 1.5
HD 3003 <sup>b</sup>	230	6.7	0.14
HD 11507	< 135	> 0.9	> 0.08
BD+40°2208	< 90	> 4.9	> 0.15
HD 82443	< 130	> 3.2	> 0.18
HD 84075	< 80	> 14	> 0.23
HD 95650	< 150	> 0.5	> 0.04
BD+21°2486	< 95	> 3.3	> 0.18
HD 124498	< 70	> 4.1	> 0.16
HD 177171	< 220	> 7.3	> 0.14
HD 180134	< 145	> 8.6	> 0.19
HD 192263	< 90	> 5.2	> 0.26
HD 202917	< 90	> 7.4	> 0.16
HD 218340	< 70	> 17	> 0.31

<sup>a</sup>The limit for  $T_D$  is calculated from the IR excess measured at 70  $\mu\text{m}$  and a conservative upper limit for the excess at 24  $\mu\text{m}$  (see text).

<sup>b</sup>The listed  $T_D$  is based on a Planck function fit to the *Spitzer* photometry corrected for the contribution by the stellar photosphere.

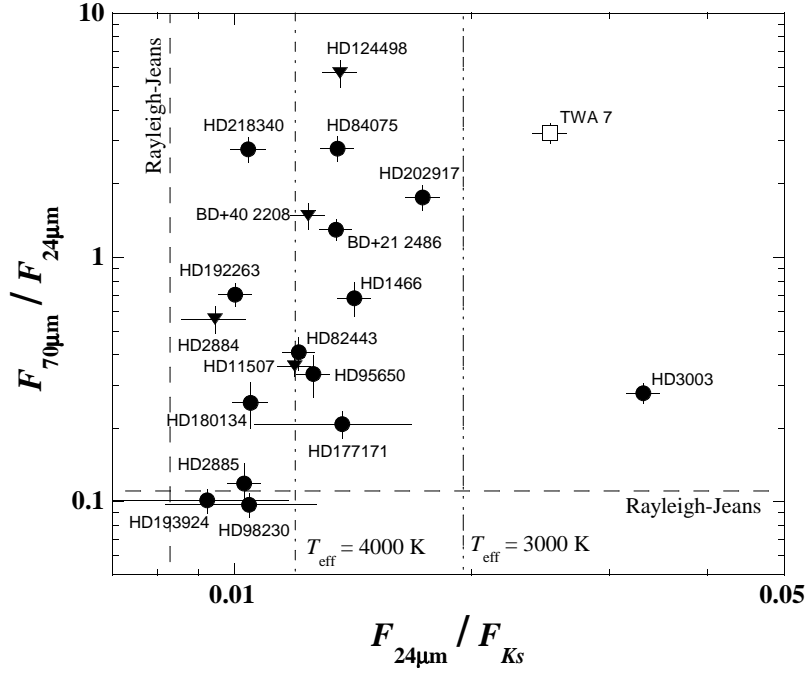


FIG. 1.— MIPS photometry compared to the 2MASS  $K_s$ -band measurements of the stellar sample. The dashed lines represent the  $F_{24\mu\text{m}}$ -to- $F_{Ks}$  and  $F_{70\mu\text{m}}$ -to- $F_{24\mu\text{m}}$  flux density ratios in the limit where the photometric bands lie along the Rayleigh-Jeans tail of the stellar spectrum. This is a poor approximation in the case of  $F_{24\mu\text{m}}/F_{Ks}$  for most stars and, therefore, the ratios based on photospheric models for  $T_{\text{eff}} = 3000$  K and 4000 K are also shown. *Triangles* represent upper limits to  $F_{70\mu\text{m}}/F_{24\mu\text{m}}$  for four stars that are likely to include flux from background sources in the measurements of  $F_{70\mu\text{m}}$  (see §2).

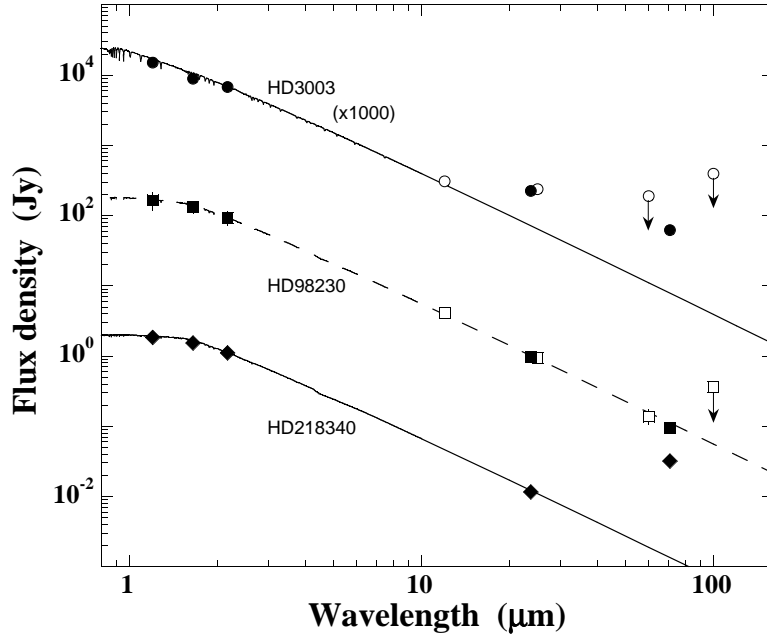


FIG. 2.— Broad-band IR spectra of three objects detected at 70  $\mu\text{m}$ . *Spitzer* and 2MASS photometry is represented by *filled* symbols, and *IRAS* measurements are shown as *open* symbols. The *IRAS* data are from the *IRAS* Faint Source Catalog (Moshir et al. 1992) and are color corrected unless the displayed point represents an upper limit to the flux density (*arrows*). Also shown is a photospheric model (Kurucz 1979) for each star that is based on the 2MASS photometry and the stellar spectral type. HD 218340 has one of the largest 70  $\mu\text{m}$  excesses in the sample, whereas the IR emission from HD 98230 is dominated by the stellar photosphere out to 70  $\mu\text{m}$ . For clarity, the spectrum for HD 3003 has been scaled by a factor of 1000, so for this object, the flux density is in units of milli-Janskys.